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CONTRIBUTIONS FROM THE CHEMICAL LABORATORY OF  
HARVARD COLLEGE.

A TABLE OF ATOMIC WEIGHTS.

BY THEODORE WILLIAM RICHARDS.

Presented March 9, 1898.

SINCE no natural constants are more used by chemists than the atomic weights, it is a matter of great importance for every one, from the chemical philosopher to the practical analyst, to have a convenient table of them always at hand. Unfortunately the present state of our science makes the selection of the values often a matter of personal opinion; and because this is the case, it is well that many of those who have had experience in accurate quantitative analysis should express their views. Hence arose the present work, which was begun solely for use in Harvard College.

It is true that an accurate table of atomic weights may sometimes be less appropriate for the calculation of analyses than an inaccurate one. For the constant errors of any one process are eliminated as much as possible from the accurate table, and, moreover, all the results are reduced to the vacuum standard. Of course neither of these refinements is to be expected in common work, although many uncorrected methods may yield results which are very consistent among themselves. Obviously the best table for the practical calculation of analyses would be a list of factors, in which each quantity had been found empirically according to precisely the method which is to be employed in the analysis of an unknown substance.\* Since, however, the errors of ordinary work often eliminate one another, and since such a table of empirical factors would have to be accompanied by exceedingly minute directions, the scientifically accurate table of atomic weights is generally the most convenient substitute for the factors demanded by the analyst, as well as the most suitable basis for theoretical considerations concerning the periodic system of the elements.

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\* Compare Seubert, *Berichte d. d. chem. Gesell.*, XXI. 2180.

In the compilation of the following table the chief emphasis has been laid on the probable chemical accuracy of the processes involved in each case. The search for possible causes of constant chemical error has usually furnished the evidence, if any evidence was to be obtained, upon which has been based the sometimes very puzzling decisions between conflicting data. For example, the possible occlusion of foreign matters by many precipitates has always been borne in mind, as well as the fact that crystals obtained from aqueous solutions usually retain with great obstinacy important amounts of mother liquor enclosed within their structure. Oxides and other substances obtained by ignition often have a tendency to occlude traces of other materials remaining from their mother compound; of course the possibilities of such a serious error must be carefully weighed in each case. Most experimenters upon the volumetric ratio of silver to the chlorides have produced erroneous data, through lack of knowledge of the dangers of this apparently simple process. These results must then be given small weight, no matter how concordant they may seem. The solubility of glass and porcelain, as well as of nearly all precipitates, is another frequently overlooked source of grave complications, and so is the action of many substances upon their containing vessels at high temperatures. The fact that in some cases the necessary methods of calculation greatly magnify the experimental error was not forgotten. These and many other equally obvious minor principles have served as the guides in the selection of the figures below; but of course the results cannot be considered ultimate. "Post-mortem examinations are often unable to detect the more subtle poisons." In many cases much more experimental work is needed, not only to secure new data, but also to show where the old are in error. While, however, it is very important to show such falsity, the attempt to counteract it numerically by the application of small corrections is a dangerous remedy; for minor conditions often seriously modify the minor corrections. In such cases wholly new data must usually be obtained, and these must be corrected, if correction is necessary, by him who is familiar with every step of the processes involved.

One is continually reminded, as he studies the conflicting evidence, of the words of Ostwald: "Differenzen sind nicht selten, und mahnen ernstlich an die Unvollkommenheit menschlicher Arbeit, aber auch an die Verantwortung, welcher jeder übernimmt, welcher einen numerischen Wert der Oeffentlichkeit mittheilt."\* This responsibility is not always

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\* Zeit. phys. Chem., III. 143.

calized by eager investigators, who seek to make up for a possible lack of quality by a superabundance of quantity. "A single determination, well worked out, is better than twenty incomplete ones. Too much cannot be said against the multiplication of incomplete or carelessly obtained data; for such data carry with them not only uncertainty and confusion in the present, but also additional labor for a reviser in the future."\* Every reaction must be assumed to involve some constant error, and every substance must be assumed to contain some constant impurity, until a proof of the contrary is obtained. Our wofully discordant data furnish a heavy presumption against almost any chemical method, when greater accuracy than one part in four or five hundred is desired.

The standard  $O = 16.000$  is adopted below, as likely to be the most convenient for many years to come.† The last figure of each number given in the following table cannot be considered in any case certain. It is often probably not much more than one unit in error; although the uncertainty may amount to as much as six or eight units in some cases. Of course the decimal notation does not admit of closer indications without an individual explanation in each case. For example: iron, germanium, and gallium are given in the table as 56.0, 70.0, and 72.5 respectively. The first is probably known within 0.1 or 0.2, while the other two may easily be 0.5 in error; but the method of expressing the results does not admit of this grade of distinction.

The aim has been to construct a convenient working table, which shall carry with it all that is trustworthy, and nothing that is unnecessary. It is almost needless to state that the well known standard works of Clarke, Meyer and Seubert, Ostwald, Van der Plaats, and others, have been freely consulted in the preparation of this table, as well as many of the original papers.

Especially am I indebted to Professor Clarke for his last gigantic collection of data and results,‡ which would have made the present table a work of supererogation, if he had viewed the subject from a somewhat less mathematical standpoint. Professor Clarke's method of decision places the credit with the skilful manipulator; I have striven to give the thoughtful chemist who is not so clever with his hands the credit which I think belongs to him. The fact that the two tables usually agree is due either to the best method's having fallen into the best hands; or to Professor Clarke's having wisely forsaken the rigid application of his

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\* These Proceedings, XXXI. 99; XXVI. 294.

† Compare F. W. Küster, *Zeit. Anorg. Chem.*, XIV. 251.

‡ *Smithson. Misc. Coll., Constants of Nature*, V. (1897.)

principle; or else, especially in the case of the rare metals, to the lack of data affording room for intelligent difference of opinion. Among the seventy-four atomic weights given in the table, only seven differ enough from the values computed by Clarke to excite remark. It seems fitting to give a brief statement of the reasons for the differences in these seven cases, leaving the details of reasoning about the other sixty-seven elements unpublished. The elements mentioned are antimony, cadmium, calcium, magnesium, platinum, tungsten, and uranium.

It is not my purpose to enter at length into the discussion of the antimony problem. Much of the voluminous work upon this subject is now rejected by common consent. The work of Bongartz,\* sometimes accepted as the best because it is the most recent, has the grave faults inherent in all methods which involve the precipitation of baric sulphate. Among all the published data Cooke's analyses of antimonious bromide † ( $\text{Sb} = 119.92$ ) seem to me the most satisfactory, because of the admirable fitness of argentic bromide for quantitative work, and because of the many precautions used in both preparation and analysis. Cooke's † and Schneider's ‡ work upon the sulphide ( $\text{Sb} = 120.5$ ) are perhaps the next in order; but Cooke's work upon this subject was far less satisfactory than his work on the bromide. Accordingly, the value 120.0 is given as the atomic weight of antimony in the accompanying table, instead of 120.43, computed by Clarke.

Although the atomic weight of cadmium has been the subject of many investigations, it is still far from certainly established. Many reasons combine to make me think that the highest of the published values are the most accurate. Dumas's § work upon the chloride of cadmium led to the value 112.23; but his method of investigating chlorides sometimes gave him too low results. || V. Hauer ¶ and Partridge \*\* found cadmium equal to less than 112 by heating cadmic sulphate in a stream of hydric sulphide, but there is no proof that their initial substance was thoroughly dried. On the other hand, Bucher's conversion of cadmic sulphate into the oxide led to the value 112.36, which Bucher regards

\* Bongartz, *Berichte d. d. chem. Gesell.*, XVI. 1942. (1883.)

† Cooke, *Proc. Am. Acad.*, V. 13. (1877.)

‡ Schneider, *Pogg. Ann.*, XCVIII. 293 (1856); *Journal prakt. Chem.*, (2), XXII. 131. (1880.)

§ Dumas, *Ann. Chem. Pharm.*, CXIII. 27. (1860.)

|| See these Proceedings, XXX. 371. Cases in point: barium, strontium, sodium, and tin.

¶ Von Hauer, *Journ. prakt. Chem.*, LXXII. 350. (1857.)

\*\* Partridge, *Am. Journ. Sci.*, (3), XL. 377. (1890.)

as the minimum.\* This method is one in which the tendency of the oxide to retain sulphuric acid is approximately neutralized by the tendency of the sulphate to retain water; this fact, which is testified by Baubigny's † good results on zinc, nickel, and aluminium, as well as Marignac's on magnesium.‡ The results of Lenssen,§ Partridge, Morse and Jones,|| and Bucher, involving the use of cadmic oxalate, all in the neighborhood of 112, are likely to be too low because of the great difficulty of freeing this substance from water. Morse and Jones have clearly indicated this and other possible causes of error. Moreover, I doubt very much if it is possible to prepare the oxalate free from the nitrate by precipitation from solutions containing cadmic nitrate. The method of calculation magnifies either error by introducing it in opposite directions into the numerator and denominator. Bucher's extended work casts grave doubt upon cadmic oxide (used by Morse and Jones, and Lorimer and Smith ¶) as a suitable substance to serve for a basis of operations. On the other hand, the work of Huntington \*\* and Bucher with the bromide (a very satisfactory substance as to its preparation because it may be sublimed, and as to its analysis because of the insolubility of argentic bromide), and that of Bucher with cadmic chloride, point toward 112.3 or 112.4 as the probable figure. The electrolytic work of Hardin †† upon these compounds, performed unfortunately with small amounts of material, is nevertheless in favor of the lower value, 112.0; so that any value adopted must be uncertain. Clarke computes 111.95; for the following table 112.3 has been chosen.

There is good reason for believing that Clarke's value for calcium (40.07) is probably too high. The only determinations worth considering are those of Erdmann and Marchand upon the composition of Iceland spar, and only one out of their thirteen experiments is corrected for known causes of constant error.‡‡ This experiment, which really constitutes the sum and substance of our pseudo-accurate knowledge of a very important quantity, makes calcium almost exactly 40.0.

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\* J. E. Bucher, Johns Hopkins Inaug. Dissertation, Baltimore. (1892.)

† Baubigny, *Compt. Rend.*, XCVII. 906, 951, 1869. (1883.)

‡ Marignac, see under magnesium, later in this paper. Compare These Proceedings, XXVI. 260, 273; XXXI. 160.

§ Lenssen, *Journ. prakt. Chem.*, LXXIX. 281. (1860.)

|| Morse and Jones, *Am. Chem. Journ.*, XIV. 260.

¶ Lorimer and Smith, *Zeit. Anorg. Chem.*, I. 364.

\*\* These Proceedings, (1881,) p. 28.

†† Hardin, *Journ. Am. Chem. Soc.*, XVIII. 1016. (1096.)

‡‡ Erdmann and Marchand, *Journ. prakt. Chem.*, L. 237. (1850.)

Obviously but little confidence may be placed in such meagre material; it is surprising enough that so common an element has remained forty years untouched on so unsatisfactory a basis. An extended investigation, now well advanced in this Laboratory, has as its object the securing of less impeachable data upon the atomic weight of this frequently appearing constituent of the universe.

Marignac's\* results from the quantitative ignition and synthesis of magnesian sulphate, processes in which the constant errors are likely to eliminate one another, have been so completely confirmed by the recent work of Richards and Parker,† that magnesium is represented by the figure 24.36 in the table. The results of the syntheses of magnesian oxide by Burton and Vorce‡ have been shown by Richards and Rogers§ to be under the cloud of a serious possible constant error, and no other results offer weighty evidence against the value just named.

An important deviation from the usually accepted figures is to be seen in the value assigned to platinum below. Our knowledge of the atomic weight of this element depends chiefly upon the elaborate and carefully executed work of Seubert|| and Halberstadt,¶ and the only question is how this is to be interpreted. These chemists studied the platinumchlorides and platinumbromides of potassium and the platinumchloride of ammonium, weighing these compounds and some of the products of their decomposition. The careful study of the results shows at once that some source of error lies hidden in all the data, for the various ratios are not wholly consistent, even in any one series. Any value from 194.7 to 196. may be obtained from the figures,\*\* the results of Seubert's work being the least discordant among themselves. Dittmar and M'Arthur†† explain the discrepancies in the case of potassic platinumchloride by assuming that the complex salt contains traces of hydroxyl replacing the halogen and traces of hydrogen replacing the potassium, as well as a small amount of extra occluded potassic chloride. They

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\* Marignac, Arch. Sci. Phys. et Nat., (3), X. 206.

† Richards and Parker, These Proceedings, XXXII. 53; Zeit. Anorg. Chem. XIII. 81. (1896.)

‡ Burton and Vorce, Am. Ch. Journ., XII. 219. (1890.)

§ Richards and Rogers, These Proceedings, XXVIII. 200.

|| Seubert, Ber. d. d. chem. Gesell., XIV. 865. (1881.)

¶ Halberstadt, Ibid., XVII. 2962. (1884.)

\*\* Clarke, Recalculation, (1897,) p. 334.

†† Trans. Roy. Soc. Edinburgh, XXXIII. Part II. 561. (1887.)

adduce experimental evidence in proof of this view, but Seubert showed in his reply \* that their hypotheses can hardly be applied to his determinations. Most of Seubert's and Halberstadt's inconsistencies may be explained by the supposition that the complex salts, like all substances crystallized from aqueous solution, contain traces of mother liquor held in minute cells within the crystal structure, and that these traces of water are not set free until the substance is disintegrated. I have accumulated a large amount of experimental evidence, soon to be published, upon this subject. Water is one of the most dangerous, although one of the least heeded, impurities in this kind of work; and in my opinion it is responsible for the lack of agreement in this case. Hence the best data for the calculation of the atomic weight of platinum seem to be those concerning the relation of the metallic platinum to the potassic chloride or potassic bromide formed by the decomposition of the complex salts; for the water must surely have been expelled from these products of the ignition. According to Clarke † potassic platinum-chloride yields 40.101 per cent of platinum and 30.671 per cent of potassic chloride, — the means of the closely agreeing results of Seubert and Halberstadt, — while according to Halberstadt potassic platinumbromide yields 25.915 per cent of platinum and 31.591 per cent of potassic bromide. Disregarding the weight of the complex salt, and assuming that  $KCl = 74.595$ , and  $KBr = 119.095$ , it is easy to calculate the respective values 195.06 and 195.39 for platinum. The mean of these two values, 195.2, is given below, instead of Clarke's 194.89. The possible occlusion of potassic halide by the complex salt may render even 195.2 too low; but more investigation is evidently needed to prove this.

The same errors may enter into the work on other platinum metals; indeed Seubert ‡ admits that traces of water were contained in some of his salts, but he applies no correction for this serious cause of inaccuracy. Since, however, Clarke's method of combining the discordant results seems more nearly to eliminate the error in these cases, his values for these elements are but little changed in the following table.

Feeling wholly unable to decide the present controversy between the two conflicting values (184.9 and 184.0) now proposed for tungsten, I have chosen the mean, 184.4, as a compromise which cannot be much more than 0.3 per cent out of the way.§

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\* Berichte d. d. chem. Gesell., XXI. 2179.

† Recalculation, page 333.

‡ Liebig's Annalen, CCLXI. 262.

§ Compare Hardin, Journ. Am. Ch. Soc., XIX. 657. (1897.)

Uranium, the highest of all the atomic weights, is one of the least satisfactorily determined. Recent investigation upon this subject at Harvard seems to show that all the published data are complicated by constant errors, which, however, sometimes partly eliminate one another; accordingly the round number 240, instead of Clarke's 239.59, is printed in the table. The discussion is better deferred until our work has taken more definite shape.

Besides these seven elements, there are seventeen more whose atomic weights, as given in the following table, differ from the results of Professor Clarke's computations by one part in a thousand or more. As none of the seventeen values is known certainly to within one part in five hundred, and some of them are probably at least as much as one per cent in error, differences in these cases will excite no especial remark. The elements are: cerium, columbium, erbium, gadolinium, gallium, glucinum, indium, lanthanum, neodymium, osmium, palladium, praseodymium, samarium, scandium, thorium, ytterbium, and zirconium. This is by no means a complete list of the uncertain elements, but only of those for which the data admit of slightly different interpretations.

It is rather unfortunate that most classified tables of the elements omit the fractional parts of the atomic weights, for these fractions will undoubtedly play an essential part in the ultimate solution of the de-Chancourtois-Newlands-Mendeléeve-Meyer mystery. In order to present a modern table which will supply these omissions, as well as afford at a glance an approximate idea of the probable error in each case, I have repeated the values in the natural order. From the classified table have been omitted several elements whose atomic weights and properties are uncertain; their presence in the system serves rather to obscure well known relations than to elucidate new ones. That this procedure is an admission of incompleteness is evident; the last part of the table is at best a lame affair. The form proposed by Thomsen\* is perhaps the most generally satisfactory of the current modes of arrangement, but his last row is unwieldy both for printing and for thinking. In the accompanying table a compromise has been adopted which cannot fail to be comprehensible; it is not my purpose here to enter into the arguments regarding the adequacy of the various forms.

This table will be reprinted, with any changes which may be necessary, every year. Since the commencement of the work I have been glad to hear of the appointment of a committee by the German

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\* Zeit. Anorg. Chem., IX. 190.

Chemical Society to accomplish a similar purpose, the American Chemical Society having for several years possessed such a committee. The matter cannot receive too much intelligent examination.

## A TABLE OF ATOMIC WEIGHTS

OF SEVENTY-FOUR ELEMENTS.

*Compiled in March, 1898, from the most Recent Data.*

Name.	Symbol.	Atomic Weight.	Name.	Symbol.	Atomic Weight.
Aluminium . .	Al	27.1	Molybdenum . .	Mo	96.0
Antimony . . .	Sb	120.0	Neodymium . .	Nd	141.
Argon . . . .	A	39.9 ?	Nickel . . . .	Ni	58.70
Arsenic . . . .	As	75.0	Niobium . . . .	Nb = Cb	94.
Barium . . . .	Ba	137.43	Nitrogen . . . .	N	14.045
Beryllium . . .	Be = Gl	9.1	Osmium . . . .	Os	190.8
Bismuth . . . .	Bi	208.	Oxygen (standard)	O	16.000
Boron . . . . .	B	10.95	Palladium . . . .	Pd	106.5
Bromine . . . .	Br	79.955	Phosphorus . . .	P	31.0
Cadmium . . . .	Cd	112.3	Platinum . . . .	Pt	195.2
Cæsium . . . . .	Cs	132.9	Potassium . . . .	K	39.140
Calcium . . . .	Ca	40.0	Praseodymium . .	Pr	144.
Carbon . . . . .	C	12.001	Rhodium . . . . .	Rh	103.0
Cerium . . . . .	Ce	140.	Rubidium . . . .	Rb	85.44
Chlorine . . . .	Cl	35.455	Ruthenium . . . .	Ru	101.7
Chromium . . . .	Cr	52.14	Samarium . . . . .	Sm	150.
Cobalt . . . . .	Co	59.00	Scandium . . . .	Sc	44.
Columbium . . .	Cb = Nb	94.	Selenium . . . . .	Se	79.0
Copper . . . . .	Cu	63.60	Silicon . . . . .	Si	28.4
"Didymium" . .	Nd + Pr	142 ±	Silver . . . . .	Ag	107.93
Erbium . . . . .	Er	166.	Sodium . . . . .	Na	23.050
Fluorine . . . .	F	19.05	Strontium . . . .	Sr	87.68
Gadolinium . . .	Gd	156. ?	Sulphur . . . . .	S	32.065
Gallium . . . . .	Ga	70.0	Tantalum . . . .	Ta	183.
Germanium . . . .	Ge	72.5	Tellurium . . . .	Te	127.5
Glucium . . . . .	Gl = Be	9.1	Terbium . . . . .	Tb	160.
Gold . . . . .	Au	197.3	Thallium . . . . .	Tl	204.15
Helium . . . . .	He	4.0 ?	Thorium . . . . .	Th	233.
Hydrogen . . . .	H	1.0075	Thulium . . . . .	Tu	170. ?
Indium . . . . .	In	114.	Tin . . . . .	Sn	119.0
Iodine . . . . .	I	126.85	Titanium . . . . .	Ti	48.17
Iridium . . . . .	Ir	193.0	Tungsten . . . . .	W	184.4
Iron . . . . .	Fe	56.0	Uranium . . . . .	U	240.
Lanthanum . . . .	La	138.5	Vanadium . . . . .	V	51.4
Lead . . . . .	Pb	206.92	Ytterbium . . . .	Yb	173.
Lithium . . . . .	Li	7.03	Yttrium . . . . .	Yt	89.0
Magnesium . . . .	Mg	24.36	Zinc . . . . .	Zn	65.40
Manganese . . . .	Mn	55.02	Zirconium . . . .	Zr	90.5
Mercury . . . .	Hg	200.0			

## THE CLASSIFICATION OF THE ELEMENTS.

H = 1.0075	Li = 7.03	Na = 23.050	K = 39.140	Rb = 85.44	Cs = 132.9	. . . .
	Be = 9.01	Mg = 24.36	Ca = 40.0	Sr = 87.68	Ba = 137.43	. . . .
	B = 10.95	Al = 27.1	Sc = 44.0	Y = 89.0	La = 138.5	. . . .
	C = 12.001	Si = 28.4	Ti = 48.17	Zr = 90.5	Ce = 140.	Th = 233.
	N = 14.045	P = 31.0	V = 51.4	Cb(Nb) = 94.	. . . .	Ta = 183.
	O = 16.000	S = 32.065	Cr = 52.14	Mo = 96.0	. . . .	W = 184.4
	F = 19.05	Cl = 35.455	Mn = 55.02	. . . .	. . . .	U = 240.
			Fe = 56.0	Ru = 101.7	. . . .	. . . .
			Co = 59.00	Rh = 103.0	. . . .	. . . .
			Ni = 58.70	Pd = 106.5	. . . .	. . . .
			Cu = 63.60	Ag = 107.93	. . . .	Au = 197.3
			Zn = 65.40	Cd = 112.3	. . . .	Hg = 200.0
			Ga = 70.0	In = 114.	. . . .	Tl = 204.15
			Ge = 72.5	Sn = 119.0	. . . .	Pb = 206.92
			As = 75.0	Sb = 120.0	. . . .	Bi = 208.
			Se = 79.0	Te = 127.5 ?	. . . .	. . . .
			Br = 79.955	I = 126.85	. . . .	. . . .

Unclassified : —

Helium = 2.0 or 4.0 ?  
 Argon = 19.94 or 39.9 ?  
 Neodymium = 141.  
 Praseodymium = 144.  
 Samarium = 150.

Gadolinium = 156.  
 Terbium = 160.  
 Erbium = 166.  
 Thulium = 170.  
 Ytterbium = 173.

Anomalous : —

Cobalt = 59.00  
 Nickel = 58.70  
 Tellurium = 127.5